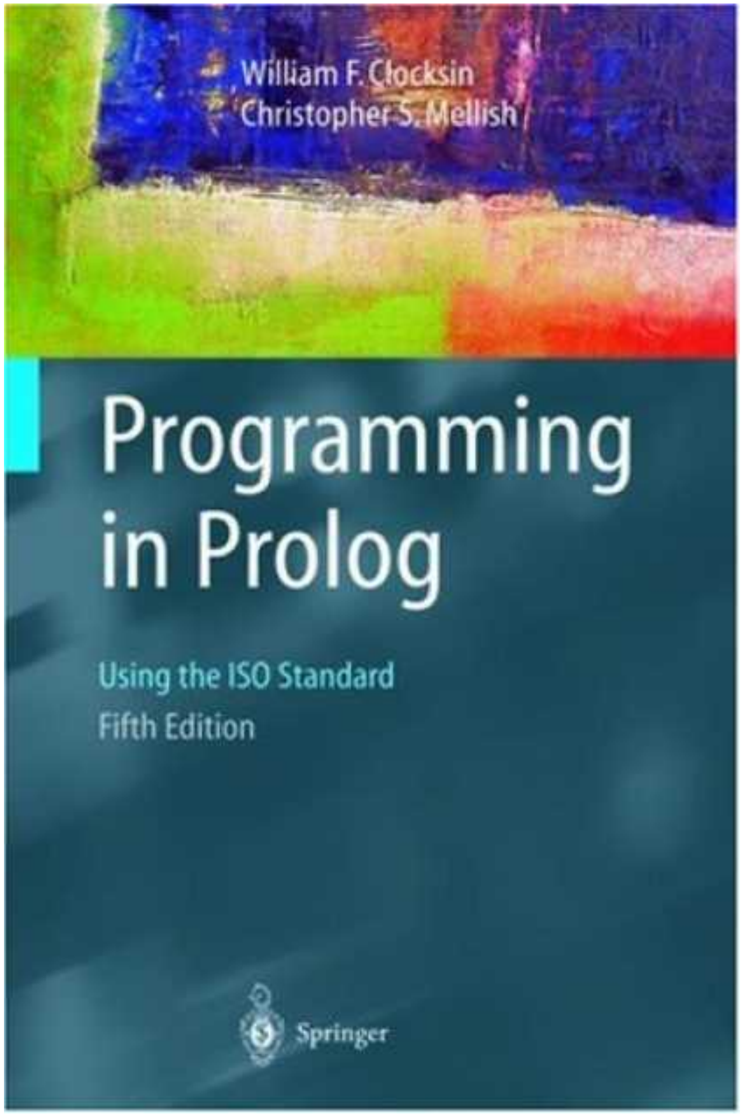
CMSC 330: Organization of Programming Languages

Logic Programming with Prolog

Background

- 1972, University of Aix-Marseille
- Original goal: Natural language processing
- At first, just an interpreter written in Algol
  - Compiler created at Univ. of Edinburgh

More Information On Prolog



- Various tutorials available online
- Links on webpage

Logic Programming

- At a high level, logic programs model the relationship between objects
  1. Programmer specifies relationships at a high level
  2. Programmer specifies basic facts
     - The facts and relationships define a kind of database
  3. Programmer then queries this database
  4. Language searches the database for answers

Features of Prolog

- Declarative
  - Facts are specified as tuples, relationships as rules
  - Queries stated as goals you want to prove, not (necessarily) how to prove them
- Dynamically typed
- Several built-in datatypes
  - Lists, numbers, records, … but no functions

Prolog not the only logic programming language

- Datalog is simpler; CLP and λProlog more feature-ful
- Erlang borrows some features from Prolog

A Small Prolog Program – Things to Notice

Use /* */ for comments, or % for 1-liners

Periods end statements

Lowercase denotes atoms

Program statements are facts and rules

Uppercase denotes variables

```
/* A small Prolog program */

% facts:
female(alice).
male(bob).
male(charlie).
father(bob, charlie).
mother(alice, charlie).

% rules for “X is a son of Y”
son(X, Y) :- father(Y, X), male(X).
son(X, Y) :- mother(Y, X), male(X).
```

Running Prolog (Interactive Mode)

Navigating location and loading program at top level

```
?- working_directory(C,C).
C = 'c:/windows/system32/'.
```

← Find current directory

```
?- working_directory(C,'c:/Users/me/desktop/p6').
C = 'c:/Users/me/desktop/'.
```

← Set directory

```
?- ['01-basics.pl'].
% 01-basics.pl compiled 0.00 sec, 17 clauses
true.
```

← Load file 01-basics.pl

```
?- make.
true.
```

← Reload modified files; replace rules

Running Prolog (Interactive Mode)

Listing rules and entering queries at top level

```
?- listing(son).
son(X, Y) :-
   father(Y, X),
   male(X).
son(X, Y) :-
   mother(Y, X),
   male(X).
true.

?- son(X,Y).
X = charlie,
Y = bob;
X = charlie,
Y = alice.
```

List rules for son

User types ; to request additional answer

Multiple answers

User types return to complete request

Quiz #1: What is the result?

Facts:

```
hobbit(frodo).
hobbit(samwise).
human(aragorn).
human(gandalf).
```

Query:

```
?- human(Z).
```

A. Z=aragorn
B. Z=aragorn; Z=gandalf.
C. Z=gandalf.
D. false.

Quiz #1: What is the result?

Facts:

```
hobbit(frodo).
hobbit(samwise).
human(aragorn).
human(gandalf).
```

Query:

```
?- human(Z).
```

A. Z=aragorn
B. Z=aragorn; Z=gandalf.
C. Z=gandalf.
D. false.

Quiz #2: What are the values of Z?

Facts:

```
hobbit(frodo).
hobbit(samwise).
human(aragorn).
human(gandalf).
taller(gandalf, aragorn).
taller(X,Y) :-
  human(X), hobbit(Y).
```

Query:

```
?- taller(gandalf,Z).
```

A. aragorn
B. frodo; samwise.
C. gandalf; aragorn.
D. aragorn;frodo;samwise.

Quiz #2: What are the values of Z?

Facts:

```
hobbit(frodo).
hobbit(samwise).
human(aragorn).
human(gandalf).
taller(gandalf, aragorn).
taller(X,Y) :-
  human(X), hobbit(Y).
```

Query:

```
?- taller(gandalf,Z).
```

A. aragorn
B. frodo; samwise.
C. gandalf; aragorn.
D. aragorn;frodo;samwise.

Outline

- Syntax, terms, examples
- Unification
- Arithmetic / evaluation
- Programming conventions
- Goal evaluation
  - Search tree, clause tree
- Lists
- Built-in operators
- Cut, negation

Prolog Syntax and Terminology

- Terms
  - Atoms: begin with a lowercase letter
    horse   underscores_ok   numbers2
  - Numbers
    123   -234   -12e-4
  - Variables: begin with uppercase or _   "don't care" variables
    X   Biggest_Animal   _the_biggest1   _
  - Compound terms: *functor*(*arguments*)
    bigger(horse, duck)
    bigger(X, duck)
    f(a, g(X, _), Y, _)

  No blank spaces between functor and (arguments)

Prolog Syntax and Terminology (cont.)

- Clauses (aka statements)
  - Facts: define predicates, terminated by a period

    ```
    bigger(horse, duck).
    bigger(duck, gnat).
    ```

    Intuitively: "this particular relationship is true"
  - Rules: *head* :- *body*

    ```
    is_bigger(X,Y) :- bigger(X,Y).
    is_bigger(X,Y) :- bigger(X,Z), is_bigger(Z,Y).
    ```

    Intuitively: "Head if Body", or "Head is true if each of the subgoals in the body can be shown to be true"
- A program is a sequence of clauses

Program Style

One predicate per line

```
blond(X) :-
    father(Father, X),
    blond(Father),        % father is blond
    mother(Mother, X),
    blond(Mother).        % and mother is blond
```

Descriptive variable names

Inline comments with % can be useful

Prolog Syntax and Terminology (cont.)

- Queries
  - To “run a program” is to submit queries to the interpreter
  - Same structure as the body of a rule
    - Predicates separated by commas, ended with a period
  - Prolog tries to determine whether or not the predicates are true

```
?- is_bigger(horse, duck).
?- is_bigger(horse, X).
```

“Does there exist a substitution for X such that is_bigger(horse,X)?”

Without which, nothing

Unification – The Sine Qua Non of Prolog

- Two terms unify if and only *if*
  - They are identical

    ?- gnat = gnat.
    true.

  - They can be made identical by substituting variables

```
?- is_bigger(X, gnat) = is_bigger(horse, gnat).
X = horse.
```

This is the substitution: what X must be for the two terms to be identical.

```
?- pred(X, 2, 2) = pred(1, Y, X)
false.
```

```
?- pred(X, 2, 2) = pred(1, Y, _)
X = 1,
Y = 2.
```

Sometimes there are multiple possible substitutions; Prolog can be asked to enumerate them all

The = Operator

- For unification (matching)
- ?- 9 = 9.
  true.
  ?- 7 + 2 = 9.
  false.
- Why? Because these terms do not match
  - 7+2 is a compound term (e.g., +(7,2))
- Prolog does not evaluate either side of =
  - Before trying to match

The is Operator

- For arithmetic operations
- LHS is RHS
  - First evaluate the RHS (and RHS only!) to value V
  - Then match: LHS = V
- Examples

```
?- 9 is 7+2.
true.

?- X = 7+2.
X = 7+2.

?- 7+2 is 9.
false.

?- X is 7+2.
X = 9.
```

The == Operator

- For identity comparisons
- X == Y
  - Returns true if and only if X and Y are identical
- Examples

```
?- 9 == 9.
true.

?- X == 9.
False.

?- X == X.
true.

?- 9 == 7+2.
false.

?- X == Y.
false.

?- 7+2 == 7+2.
true.
```

The =:= Operator

- For arithmetic operations
- "LHS =:= RHS"
  - Evaluate the LHS to value V1 (Error if not possible)
  - Evaluate the RHS to value V2 (Error if not possible)
  - Then match: V1 = V2
- Examples

```
?- 7+2 =:= 9.
true.

?- 7+2 =:= 3+6.
true.

?- X =:= 9.

?- X =:= 7+2
```

Error: =:=/2: Arguments are not sufficiently instantiated

Quiz #3: What does this evaluate to?

Query:

```
?- 9 = 7+2.
```

A. true
B. false

Quiz #3: What does this evaluate to?

Query:

```
?- 9 = 7+2.
```

A. true

B. **false**

No Mutable Variables

- = and is operators do not perform assignment
  - Variables take on exactly one value (“unified”)
- Example
  - foo(...,X) :- ... X = 1,...   % true only if X = 1
  - foo(...,X) :- ... X = 1, ..., X = 2, ...   % always fails
  - foo(...,X) :- ... X is 1,...   % true only if X = 1
  - foo(...,X) :- ... X is 1, ..., X is 2, ...   % always fails

X can’t be unified with 1 & 2 at the same time

Function Parameter & Return Value

- Code example

Parameter

Return value

```
increment(X,Y) :-
    Y is X+1.
?- increment(1,Z).
Z = 2.
?- increment(1,2).
true.
?- increment(Z,2).
ERROR: incr/2: Arguments are not sufficiently instantiated
```

Query

Result

Can't evaluate X+1 since X is not yet instantiated to int

Function Parameter & Return Value

- Code example

Parameters

Return value

```
addN(X,N,Y) :-
    Y is X+N.

?- addN(1,2,Z).      ← Query
Z = 3.               ← Result
```

Recursion

- Code example

```
addN(X,0,X).            ← Base case
addN(X,N,Y) :-          ← Inductive step
    X1 is X+1,
    N1 is N-1,
    addN(X1,N1,Y).      ← Recursive call

?- addN(1,2,Z).
Z = 3.
```

Quiz #4: What are the values of X?

Facts:

```
mystery(_,0,1).
mystery(X,1,X).
mystery(X,N,Y) :-
  N > 1,
  X1 is X*X,
  N1 is N-1,
  mystery(X1,N1,Y).
```

Query:

```
?- mystery(5,2,X).
```

A. 1.
B. 32.
C. 25.
D. 1; 25.

Quiz #4: What are the values of X?

Facts:

```
mystery(_,0,1).
mystery(X,1,X).
mystery(X,N,Y) :-
  N > 1,
  X1 is X*X,
  N1 is N-1,
  mystery(X1,N1,Y).
```

Query:

```
?- mystery(5,2,X).
```

A. 1.
B. 32.
C. 25.
D. 1; 25.

Factorial

- Code

```
factorial(0,1).
factorial(N,F) :-
    N > 0,
    N1 is N-1,
    factorial(N1,F1),
    F is N*F1.
```

Tail Recursive Factorial w/ Accumulator

- Code

```
tail_factorial(0,F,F).
tail_factorial(N,A,F) :-
    N > 0,
    A1 is N*A,
    N1 is N -1,
    tail_factorial(N1,A1,F).
```

And and Or

- And
  - To implement X && Y use , in body of clause
  - E.g., for Z to be true when X and Y are true, write

```
Z :- X,Y.
```

- Or
  - To implement X || Y use two clauses
  - E.g., for Z to be true when X or Y is true, write

```
Z :- X.
Z :- Y.
```

Goal Execution

- When submitting a query, we ask Prolog to substitute variables as necessary to make it true
- Prolog performs goal execution to find a solution
  - Start with the goal, and go through statements in order
  - Try to unify the head of a statement with the goal
  - If statement is a rule, its hypotheses become subgoals
    - Substitutions from one subgoal constrain solutions to the next
  - If goal execution reaches a dead end, it backtracks
    - Tries the next statement
  - When no statements left to try, it reports false
- More advanced topics later – cuts, negation, etc.

Goal Execution (cont.)

- Consider the following:
  - "All men are mortal"

    mortal(X) :- man(X).
  - "Socrates is a man"

    man(socrates).
  - "Is Socrates mortal?"

    ?- mortal(socrates).

    true.
- How did Prolog infer this?

1. Sets mortal(socrates) as the initial goal
2. Sees if it unifies with the head of any clause:

   mortal(socrates) = mortal(X).
3. man(socrates) becomes the new goal (since X=socrates)
4. Recursively scans through all clauses, backtracking if needed …

Clause Tree

- Clause tree
  - Shows (recursive) evaluation of all clauses
  - Shows value (instance) of variable for each clause
  - Clause tree is true if all leaves are true
- Factorial example

factorial(3,6)

```
factorial(0,1).
factorial(N,F) :-
        N > 0,
        N1 is N-1,
        factorial(N1,F1),
        F is N*F1.
```

Clause Tree

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  - Shows (recursive) evaluation of all clauses
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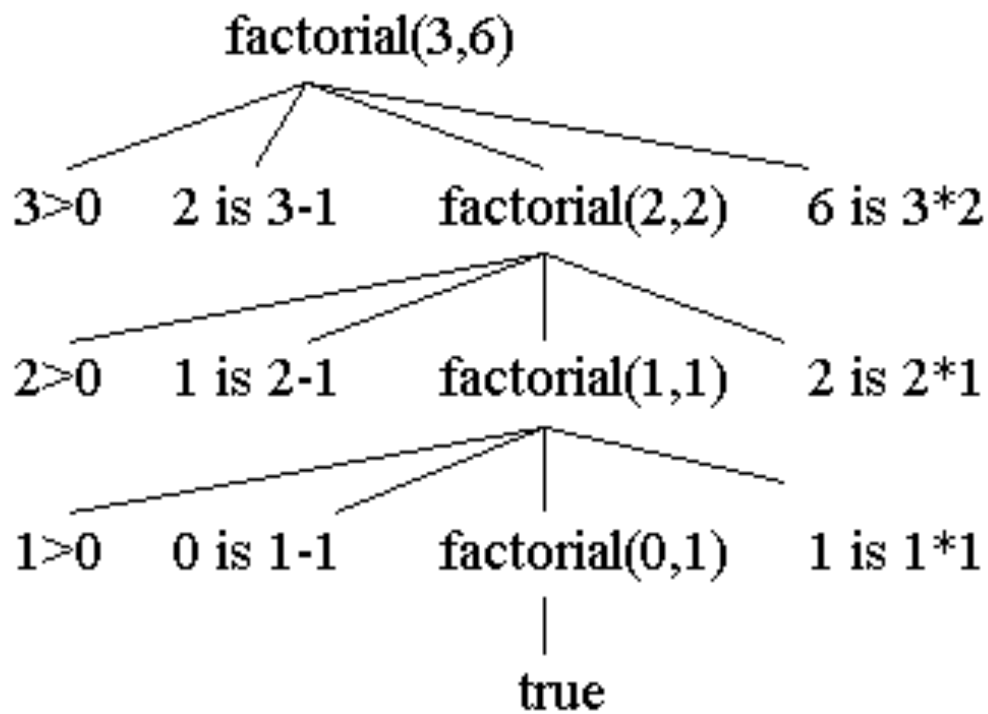
- Factorial example

```
factorial(0,1).
factorial(N,F) :-
        N > 0,
        N1 is N-1,
        factorial(N1,F1),
        F is N*F1.
```



Tracing

- trace lets you step through a goal's execution
  - notrace turns it off

```
1  my_last(X, [X]).

2  my_last(X, [_|T]) :-
           my_last(X, T).
```

```
?- trace.
true.

[trace]  ?- my_last(X, [1,2,3]).
2    Call: (6) my_last(_G2148, [1, 2, 3]) ? creep
2    Call: (7) my_last(_G2148, [2, 3]) ? creep
1    Call: (8) my_last(_G2148, [3]) ? creep
     Exit: (8) my_last(3, [3]) ? creep
     Exit: (7) my_last(3, [2, 3]) ? creep
     Exit: (6) my_last(3, [1, 2, 3]) ? creep
X = 3
```

Goal Execution – Backtracking

- Clauses are tried in order
  - If clause fails, try next clause, if available
- Example

```
jedi(luke).
jedi(yoda).
sith(vader).
sith(maul).
fight(X,Y) :- jedi(X), sith(Y).
```

```
?- fight(A,B).
A=luke,
B=vader;
A=luke,
B=maul;
A=yoda,
B=vader;
A=yoda,
B=maul.
```

Prolog (Search / Proof / Execution) Tree